PROJECT ID: EEMS020

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Multi-Scenario Assessment of Optimization Opportunities due to Connectivity and Automation

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2017 U.S. DOE Vehicle Technologies Office Annual Merit Review

JUNE 19, 2018

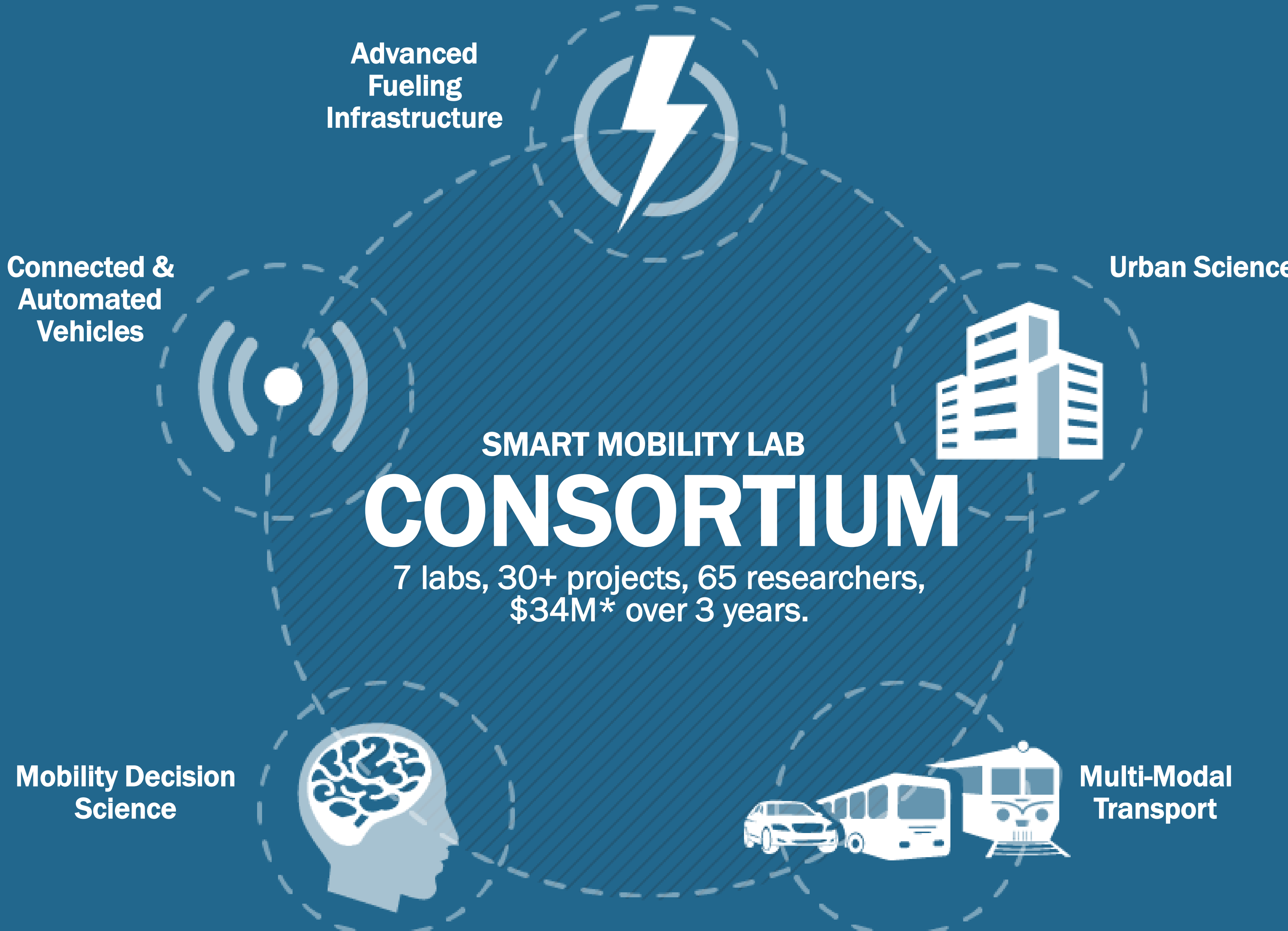
Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · BERKELEY LAB · OAK RIDGE National Laboratory · NREL NATIONAL RENEWABLE ENERGY LABORATORY

ENERGY EFFICIENT MOBILITY SYSTEMS PROGRAM INVESTIGATES

MOBILITY ENERGY PRODUCTIVITY

THROUGH FIVE EEMS ACTIVITY AREAS

- Advanced R&D Projects
- Living Labs
- Smart Mobility Lab Consortium
- Core Evaluation & Simulation Tools
- HPC4Mobility & Big Transportation Data Analytics



*Based on anticipated funding

Project Overview

Timeline

- Project start: October 1, 2016
- Project end: September 30, 2019
- Percent complete: 40%

Budget

- Total project funding
  - DOE share: 100%
  - Contractor share: 0%
- Funding received in FY 2017
  - $ 332.3
- Funding for FY 2018
  - $364K

Barriers

- Barriers addressed
  - Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles
  - Determining the value and productivity derived from new mobility technologies

Partners

- Lead: ORNL
- DOE Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Lab Consortium:
  - ANL: Argonne National Laboratory
  - NREL: National Renewable Energy Lab
  - INL: Idaho National Lab
  - LBNL: Lawrence Berkeley National Lab
- University of Delaware (Data from Human-in-the-loop testing)
- Active discussion with an OEM

Project Relevance

- **Challenge**
  - Much research in connectivity and automation is focused on safety
  - High uncertainty about energy impacts, further exploration of mobility gains & energy savings potential is needed
- **Objective:**
  - Develop optimal CAVs coordination strategies to increase mobility energy productivity in full and partial market penetration under diverse traffic scenarios; Develop simulation framework to verify effectiveness
  - FY18:
    - Extend the analysis to a highway corridor and enhance accuracy of the fuel consumption models we are currently using.
    - Explore the effects of communication instabilities and additional vehicle powertrain technologies (e.g., xEVs) on transportation system performance
- **Impacts:**
  - Contributing to the SMART Mobility program goal of yielding meaningful insights on how SMART technologies can improve Mobility Energy Productivity
    - Polynomial models for fuel/energy consumption estimation
    - Insights regarding efficient coordination/control strategies that could offer energy and mobility improvements
  - Generating a methodology to quantify the benefits of partial market penetrations of optimally coordinated CAVs to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility energy efficiency

Any proposed future work is subject to change based on funding levels

Approach

- **Develop and validate fuel consumption models for integration of additional powertrains**
  - Polynomial models based on Autonomie data

- **Expand the current optimization and simulation framework to interconnected traffic segments (highway corridor, urban area)**
  - Adapting the framework for integration of additional powertrains
  - Adding lanes (optimal lane changing)
  - Definition of optimal control zone length

- **Explore additional strategies to improve the traffic efficiency with partial penetration of CAVS**
  - Exploration of human drivers behavior

- **Analyze the impacts of communication instabilities on the system performance**
  - How the communication instabilities affect safety and efficiency?

MILESTONES

Task	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4	FY19
1. Integration of validated fuel consumption models for different powertrains					
2. Optimal coordination framework adapted to a highway corridor					
3. Impacts quantification highway corridor, heterogeneous traffic					
4. Paper reporting findings					
5. Impact assessment of communication instabilities and related issues on proposed schemes					
6. Continued assessment of optimal coordination strategies varying powertrains and penetration levels on additional traffic scenarios (urban)					

Any proposed future work is subject to change based on funding levels

Technical Accomplishments

Technical accomplishments – Summary (1)

1. Extended the simulation methodology to allow exploration of additional scenarios (slide 10)
   – Traffic demands, traffic scenarios

2. Assessed the implications of *full* penetration of optimally coordinated CAVs (slides 11 -14)
   – Merging roadways, Intersection, Roundabout and Speed reduction zones

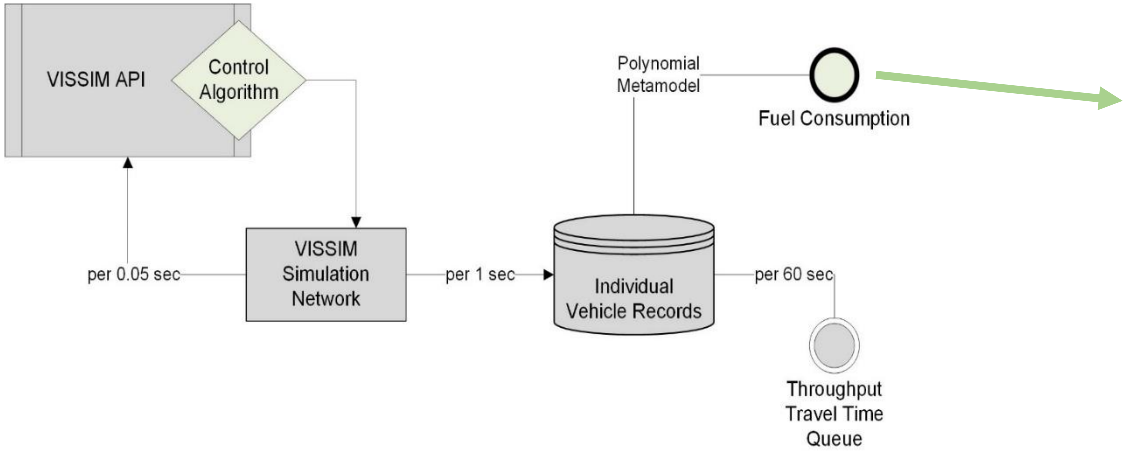
3. Novel insights on implications of *partial* penetrations of optimally coordinated CAVs (slides 15-16)
   – Merging roadways and roundabouts in mix with manually-driven vehicles

4. Developed polynomial metamodels for fuel/energy consumption estimation based on simulation data from Autonomie (slide 17)
   – Medium duty vehicle, heavy duty vehicle and electric vehicle

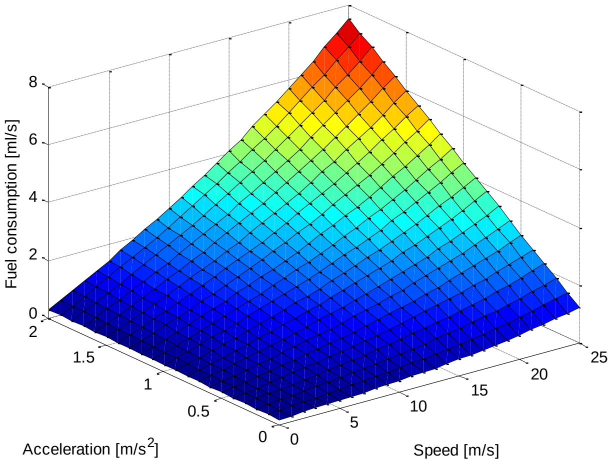
5. Ongoing (BackUp Slides)
   – Optimal solution deep dive
   – Adaptation of optimal coordination to a highway corridor

Simulation methodology was extended to allow exploration of additional traffic scenarios

- CAVs control algorithm ➔ Matlab
- Traffic simulation ➔ PTV VISSIM



Polynomial metamodel for fuel consumption estimation*



$$f_v = f_{cruise} + f_{accel},$$

$$f_{cruise} = w_0 + w_1 \cdot v + w_2 \cdot v^2 + w_3 \cdot v^3$$

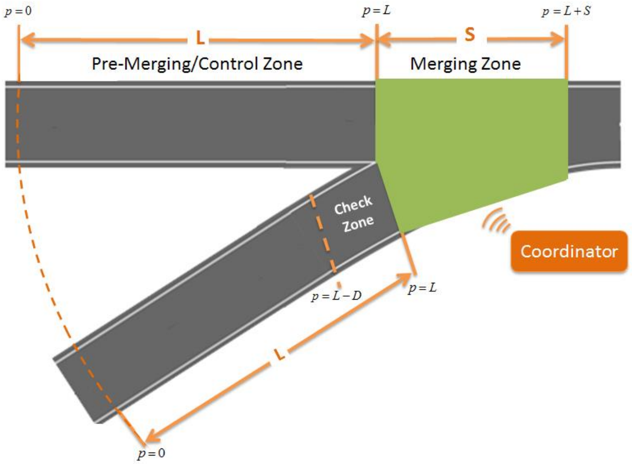
$$f_{accel} = a \cdot (r_0 + r_1 \cdot v + r_2 \cdot v^2)$$

* Fuel consumption model: M. A. S. Kamal, M. Mukai, J. Murata, and T. Kawabe, "Model Predictive Control of Vehicles on Urban Roads for Improved Fuel Economy," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 3, pp. 831–841, 2013

CAVs Optimal Coordination Algorithm reduces energy by minimizing vehicles' acceleration

Optimal control problem

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \sum_{i=1}^{n} \int_{t_i^o}^{t_i^f} u_i^2 \, dt$$



Subject to:

Vehicle dynamics

$$\dot{p}_i = v_i$$
$$\dot{v}_i = u_i,$$

Safety Constraints

$$u_i \in R_i$$
$$R_i \triangleq \{u_i(t) \in [u_{\min}, u_{\max}] \mid p_i(t) \le p_k(t) - \delta,$$
$$v_i(\mathrm{t}) \in [v_{\min}, v_{\max}], \forall i \in \mathcal{N}(t), |\mathcal{N}(t)| > 1, \forall t \in [t_i^0, t_i^f]\},$$

Where R_i *is the control interval, δ a safe headway distance and* ***k*** *the leader of vehicle* ***i****.*

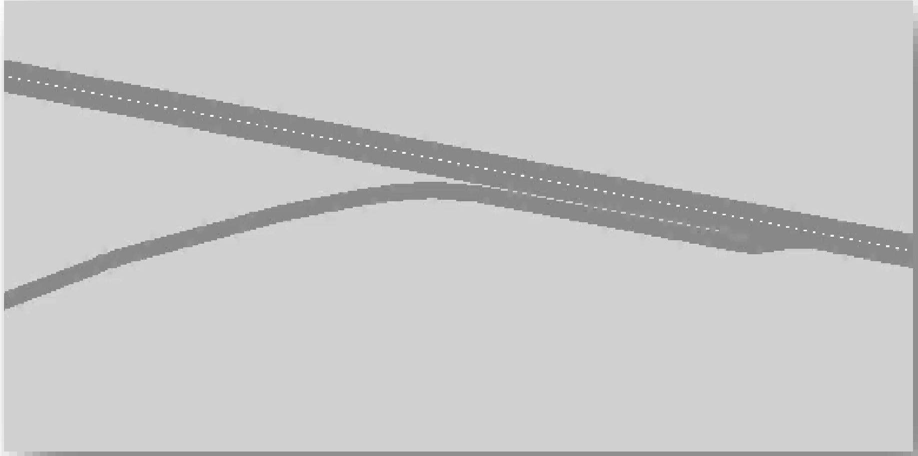
Analytical solution is found through application of Hamiltonian analysis

* ***J. Rios-Torres*** and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, April 2017. doi: 10.1109/TITS.2016.2587582

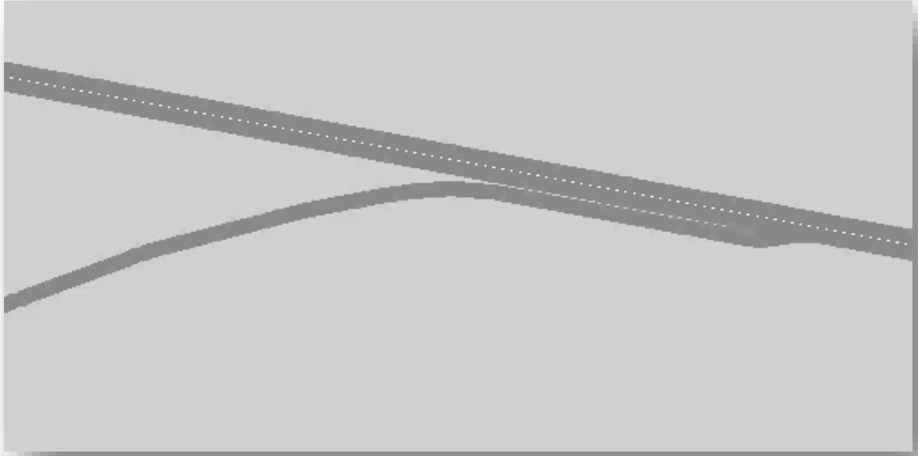
Optimal coordination enables smooth merging!

Full market penetration assessment -Merging on-ramp

Baseline



Optimal

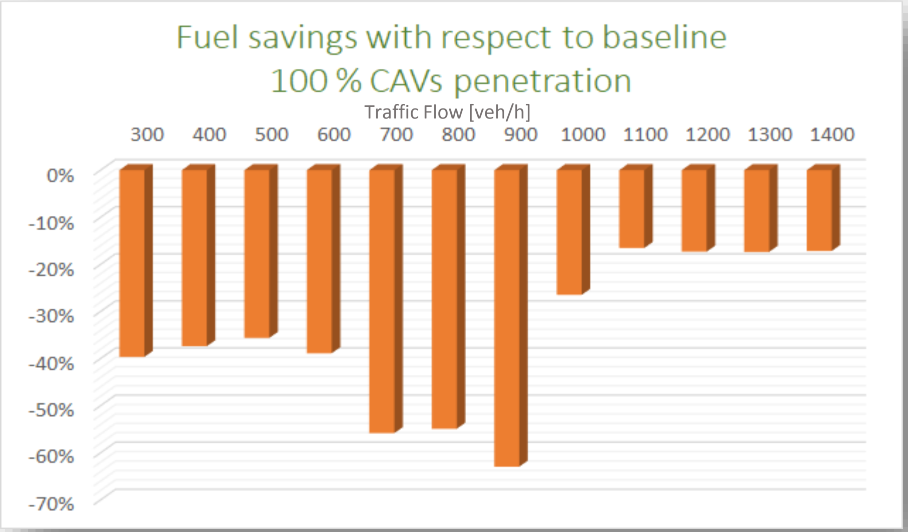


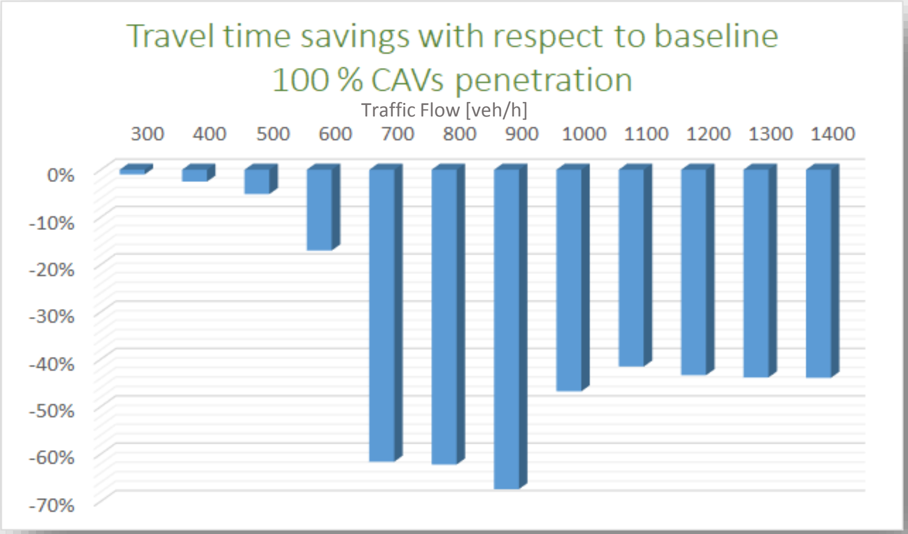
Rios-Torres, J; A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems , no.99, pp.1-10, doi: 10.1109/TITS.2016.2587582
***Rios-Torres, J*.**, and Malikopoulos, A.A., "A Survey on the Coordination of Connected and Automated Vehicles at Intersections and Merging at Highway On-Ramps," IEEE Trans. Intel. Trans. Syst., Vol. 18, 5, pp. 1066-1077, 2017

Optimal coordination enables fuel consumption savings in diverse traffic conditions (full penetration)

Full market penetration assessment -Merging on-ramp

- Significant fuel consumption savings in all traffic conditions
- Travel time savings are significant in moderate/high traffic conditions
- Time value > Fuel value





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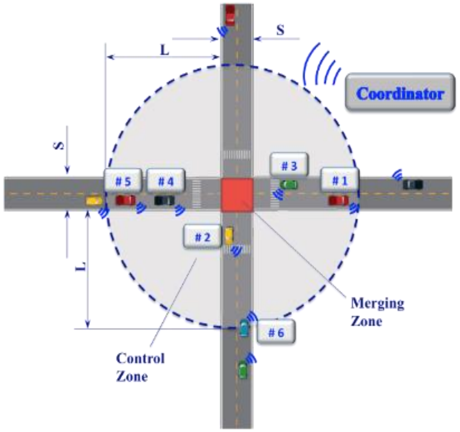
Optimal Coordination algorithm can be adapted to multiple traffic scenarios (Full penetration)

Full market penetration assessment – Other traffic scenarios

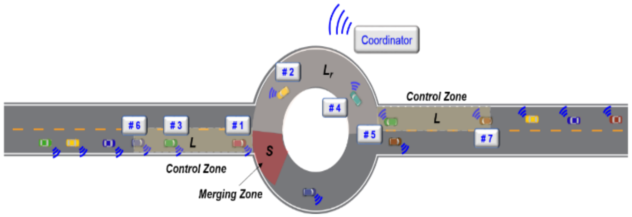
- Intersection



- Fuel consumption: up to-42%
- Travel time: up to -37%

Zhang, Y.Z, Cassandras, C.G., Malikopoulos, A.A., "*Optimal Control of Connected Automated Vehicles at Urban Traffic Intersections: A Feasibility Enforcement Analysis*," Proceedings of the 2017 American Control Conference, pp. 3548-3553, 2017. 2017

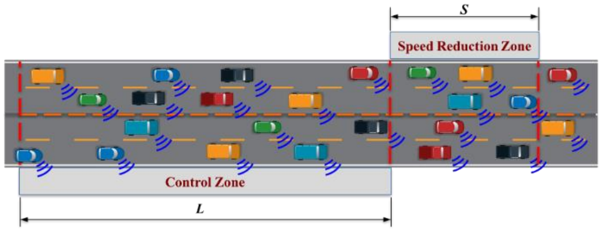
- Roundabout



- Fuel consumption: up to -27%
- Travel time: up to -49%

Luihui Zhao, Andreas Malikopoulos and ***Jackeline Rios-Torres***. "Optimal Control of Connected and Automated Vehicles at Roundabouts" 97th Annual Meeting Transportation Research Board, 2018

- Speed Harmonization



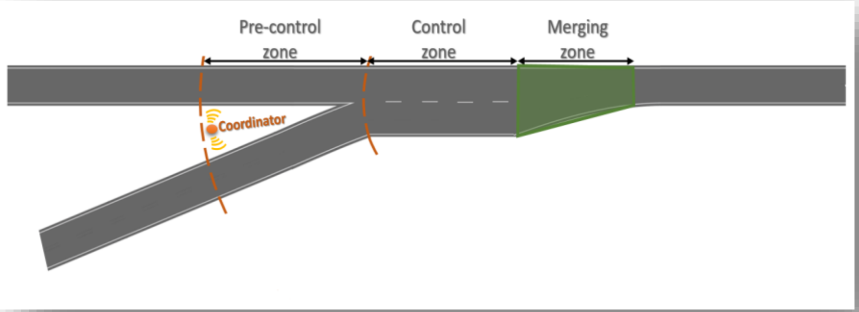
- Fuel consumption: up to -17%
- Travel time: up to -32%

Hong, S., Malikopoulos, A. A., Lee, J., and Park, B., "*Development and Evaluation of Speed Harmonization using Optimal Control Theory: A Simulation-Based Case Study at a Speed Reduction Zone*," in 96th Annual Meeting Transportation Research Board, 2017

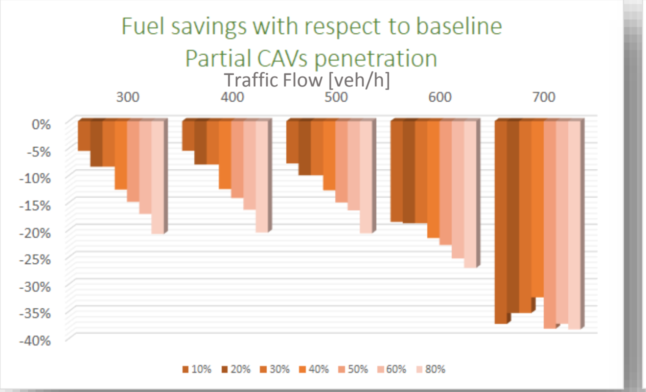
Fuel savings trends change with partial market penetration of CAVs

Partial market penetration assessment – Merging on-ramp

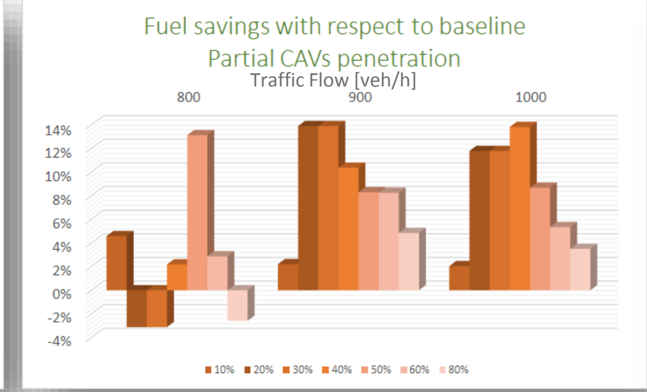
- Fuel savings for low traffic demand
- Fuel increases for medium and high traffic demand



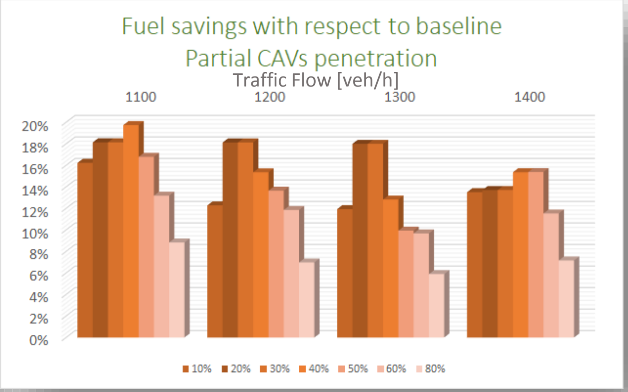
Low traffic



Medium traffic



High traffic

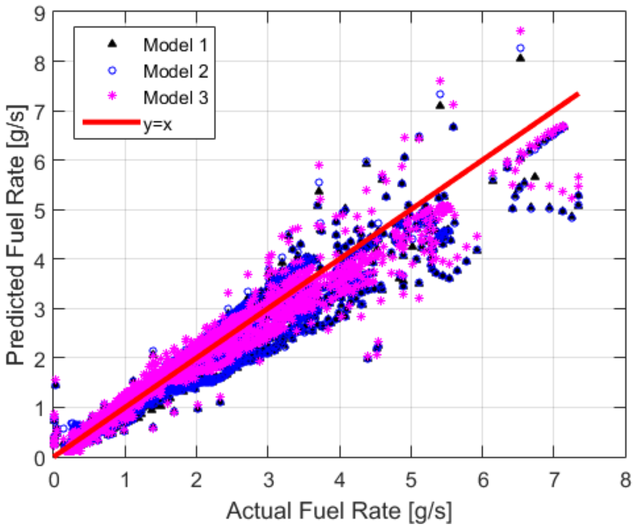


Rios-Torres, J; A. A. Malikopoulos, "Impact of Partial Penetrations of Connected and Automated Vehicles on Fuel Consumption and Traffic Flow," (*submitted*)

Compared current fuel estimation metamodel against Autonomie data

Calculated polynomial metamodels for fuel consumption estimation based on simulation data from Autonomie (case: medium duty vehicle)

- **Model 1:**
  - $f_e = p_0 + p_1 v a_d, p_0 = 0.0009, p_1 = 0.0016$
- **Model 2:**
  - $f_e = p_0 + p_1 v a_d + p_2 j_d, p_0 = 0.0007, p_1 = 0.0017, p_2 = 0.0025$
- **Model 3:**
  - $f_e = b_0 + b_1 v + b_2 v^2 + b_3 v^3 + a(c_0 + c_1 v + c_2 v^2)$
  - $b_0 = 1.04 \times 10^{-4}, b_1 = 2.23 \times 10^{-5}, b_2 = -1.49 \times 10^{-6}, b_3 = 2.99 \times 10^{-8}$
  - $c_0 = 8.67 \times 10^{-5}, b_1 = 1.42 \times 10^{-4}, b_2 = -1.16 \times 10^{-6}$



LoA* [%]	FHDS	UDDS	US06
Model 1	2.69	7.62	0.51
Model 2	2.59	7.57	0.47
Model 3	0.46	2.80	2.18

*Loss of Accuracy= $\left|\frac{(m_{f.prd} - m_{f.act})}{m_{f.act}}\right|$

Responses to previous year reviewers' comments (1)

- **The reviewer pointed out that only analyzing one traffic flow is rather simplistic.**

- **Actions taken:**
  - For our recent and coming simulation studies, we have been considering and comparing the results under multiple different traffic flow values to determine the impacts.
  - Notably, taking this new approach allowed us to find new insights, e.g., for an isolated merging scenario under heavy traffic conditions and partial market penetrations, the current optimal coordination framework will increase the fuel consumption.
  - We are currently exploring some variations to the optimal problem formulation to determine whether there are still opportunities to obtain fuel savings under the mixed and heavy traffic conditions

Responses to previous year reviewers' comments (2)

- **The reviewer gave the project a "Good" rating in this area simply because of the interaction with the SMART Mobility Consortium and with a few universities, but commented that it would help if the nature of the interactions and the roles for each participant were defined.**
- **The reviewer thought that it would also be useful for the researchers to interact with some private companies who have an interest in the results of this work. Whether the companies involved with automated vehicles (Google, Uber, Big 3, etc.) would participate is an open question, but it would be good to know that they were contacted. The reviewer pointed out that interactions with some private companies would add some immediate and long-term relevance to the work.**

- **Actions taken:**
  - Participating with other SMART Mobility research teams/models to structure interactions of this project with others, identifying data flows and contributions to overall SMART Mobility combined assessment of Mobility Energy Productivity
  - Active discussions with an OEM on potential collaboration for some validation work. We have also held discussions with Lyft (potential for data sharing).
  - Ongoing efforts to explore the implications of having optimal coordination of connected and automated heavy duty vehicles in full penetration scenarios and in mixed traffic scenarios (including light duty human-driven vehicles)

Collaboration and coordination with other institutions

- **SMART Mobility Consortia:**

- **University Collaboration:**

Subcontractor, human-in-the-loop data for validation

Active discussions on communication-related challenges

- **Active discussions with an OEM for possible validation**

Remaining challenges and barriers

- **Control problem formulation**
  – Adaptation to interconnected scenarios, definition of optimal control zone length needs further exploration for different traffic scenarios
  – Lane change considerations in the context of the optimal coordination framework

- **Calibration**
  – Real traffic data is required to analyze the impacts of optimization opportunities in real traffic scenarios

- **Human behavior**
  – Well known driver models may not fully represent the behavior of human drivers + diversity

- **Diversity in actual traffic scenarios**
  – Need to represent agents diversity (powertrain types, driver diversity, etc.)

Future work

- **Ongoing**
  - FY18: Analysis of traffic flow/time/energy implications considering:
    - Multiple lanes
    - Heterogeneous traffic (Trucks, EVs, conventional)
    - Interconnected scenarios (Highway corridor)
    - Partial market penetrations

Savings trends/numbers may vary when analyzing interconnected scenarios

- **Proposed**
  - FY19: Continued analysis of time/energy implications considering
    - Interconnected scenarios (Urban area with interconnected intersections, roundabouts, speed reduction zones)
    - Effects of communication instabilities
    - Validation with human-in-the-loop

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Project supports the objective of the DOE SMART consortia to explore opportunities to enhance mobility and reduced energy use in transportation through development and analysis of optimal CAVs coordination strategies.
- **Approach:**
  - Apply optimal control theory to develop and assess optimal CAVs coordination algorithms adaptable to multiple traffic scenarios and powertrain types.
  - Generate a methodology to assess the benefits of partial market penetrations of optimally coordinated CAVs to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility energy productivity
- **Collaborations:** SMART Mobility Consortium, University of Delaware (active discussions with OEM and UTK)
- **Technical Accomplishments:**
  - Assessed fuel consumption and travel time impacts of optimal CAVs coordination in multiple isolated traffic scenarios under different traffic conditions and market penetration rates. The simulation results indicate
    - Full penetration rate of optimally coordinated CAVs show significant fuel consumption and travel time savings
    - Partial penetration rates of optimally coordinated CAVs contributes to significant fuel savings under low traffic conditions but the fuel consumption can increase under heavy traffic
- **Future Work:**
  - Further analysis of time/energy implications considering Interconnected scenarios (urban area)
  - Effects of communication instabilities
  - Strategies to improve efficiency under partial penetration and heavy traffic conditions
  - Validation with human and hardware-in-the-loop

Any proposed future work is subject to change based on funding levels

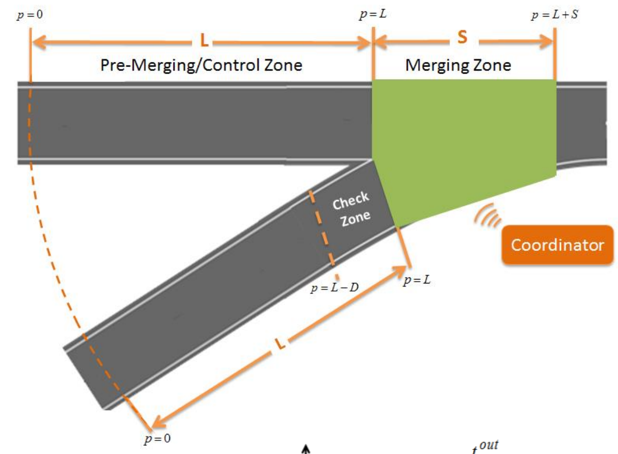
QUESTIONS?

Technical Back-Up Slides

Technical accomplishments (2)

Optimal control problem

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \sum_{i=1}^{n} \int_{t_i^o}^{t_i^f} u_i^2 \, dt$$



Subject to:

Vehicle dynamics

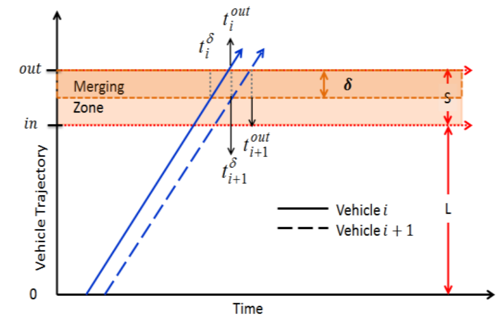
$$\dot{p}_i = v_i$$
$$\dot{v}_i = u_i,$$

Safety Constraints

$$u_i \in R_i$$

$$R_i \triangleq \{u_i(t) \in [u_{\min}, u_{\max}] \mid p_i(t) \le p_k(t) - \delta,$$
$$v_i(\mathrm{t}) \in [v_{\min}, v_{\max}], \forall i \in \mathcal{N}(t), |\mathcal{N}(t)| > 1, \forall t \in [t_i^0, t_i^f]\},$$

Where R_i *is the control interval,* δ *a safe headway distance and* ***k*** *the leader of vehicle* ***i****.*



Hamiltonian analysis allows to find the analytical solution of the unconstrained problem

* ***J. Rios-Torres*** and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, April 2017. doi: 10.1109/TITS.2016.2587582

Unconstrained optimal control problem -analytical solution

The optimal control input and states are obtained as a function of time and some vehicle specific constants a, b, c, d:

$$u_i^*(t) = a_i t + b_i$$ Optimal Acceleration

$$v_i^*(t) = \frac{1}{2} a_i t^2 + b_i t + c_i$$ Optimal Speed

$$p_i^*(t) = \frac{1}{6} a_i t^3 + \frac{1}{2} b_i t^2 + c_i t + d_i$$ Optimal Position

The system of equations allows the implementation of a real-time optimal controller:

$$\begin{bmatrix} \frac{1}{6}(t)^3 & \frac{1}{2}(t)^2 & t & 1 \\ \frac{1}{2}(t)^2 & t & 1 & 0 \\ \frac{1}{6}(t_i^f)^3 & \frac{1}{2}(t_i^f)^2 & t_i^f & 1 \\ \frac{1}{2}(t_i^f)^2 & t_i^f & 1 & 0 \end{bmatrix} \begin{bmatrix} a_i \\ b_i \\ c_i \\ d_i \end{bmatrix} = \begin{bmatrix} p_i(t) \\ v_i(t) \\ p_i(t_i^f) \\ v_i(t_i^f) \end{bmatrix}$$

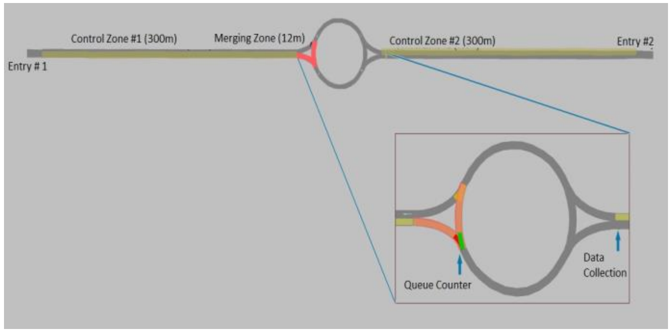
The system of equations can be solved at each instant of time

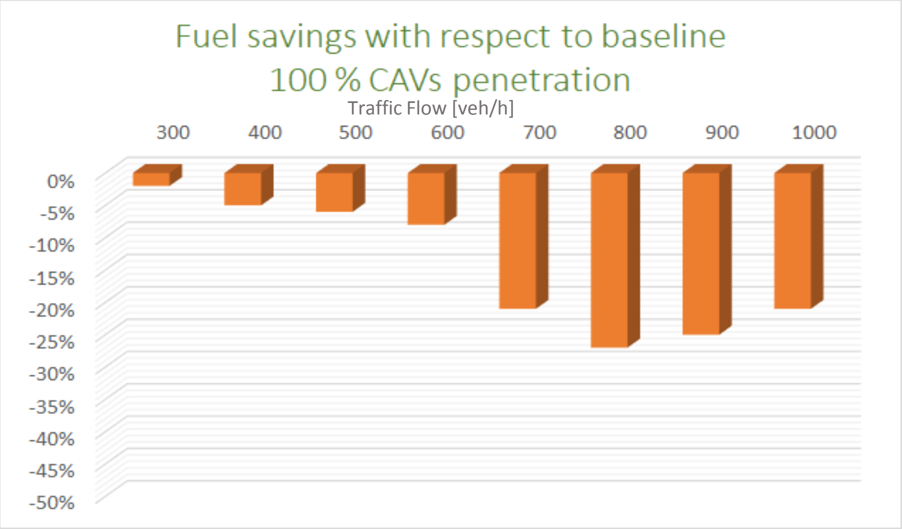
CLOSED LOOP SOLUTION!!!

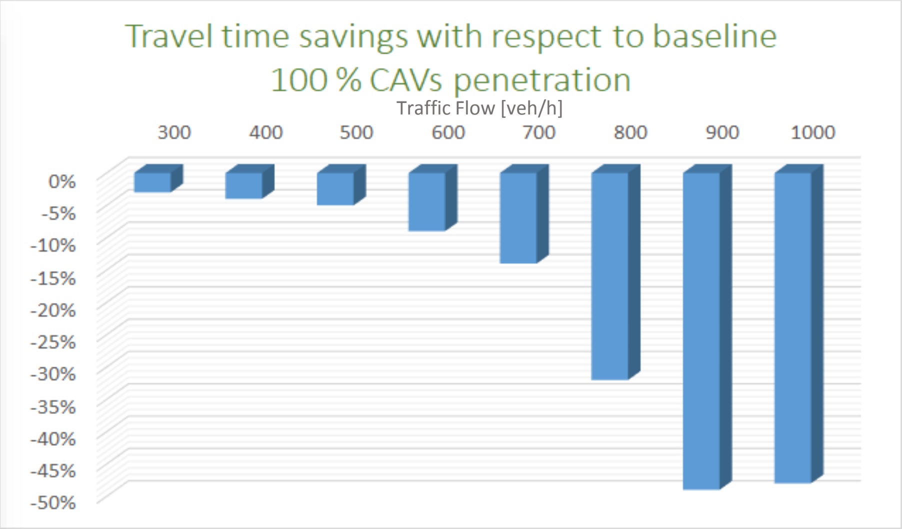
* ***J. Rios-Torres*** and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, 2017. doi: 10.1109/TITS.2016.2587582

Full market penetration assessment - Roundabout

- Fuel consumption savings in all traffic conditions
- Travel time savings are significant in moderate/high traffic conditions







Luihui Zhao, Andreas Malikopoulos and ***Jackeline Rios-Torres***. "Optimal Control of Connected and Automated Vehicles at Roundabouts" 97th Transportation Research Board Annual Meeting , 2018

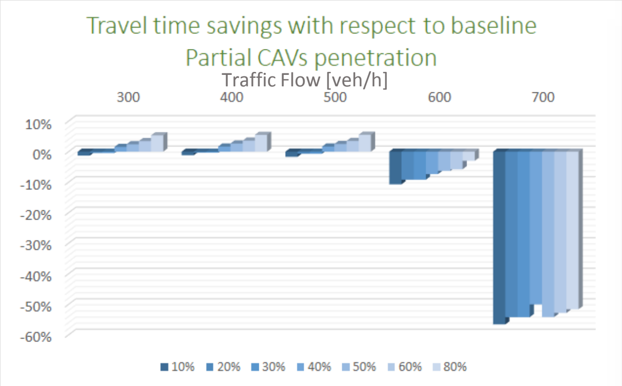
Partial market penetration assessment – Merging on-ramp

Partial market penetration assessment – Merging on-ramp

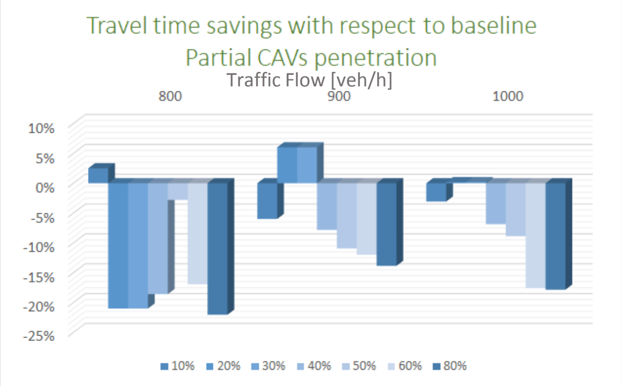
Travel time

- Remains almost constant for very low traffic demand
- Travel time savings observed for most scenarios in moderate traffic
- Travel time savings at high traffic demand when there is more than 40% CAVs

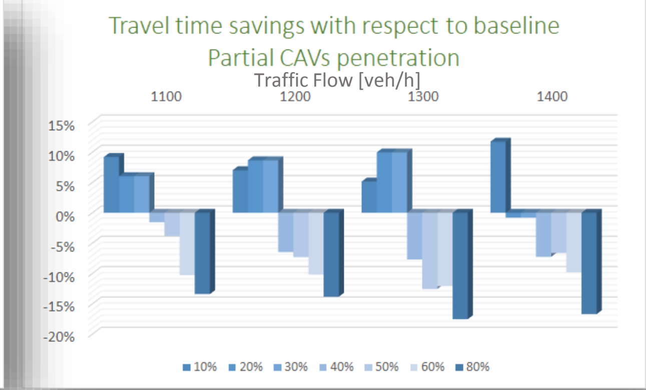
Low traffic



Medium traffic



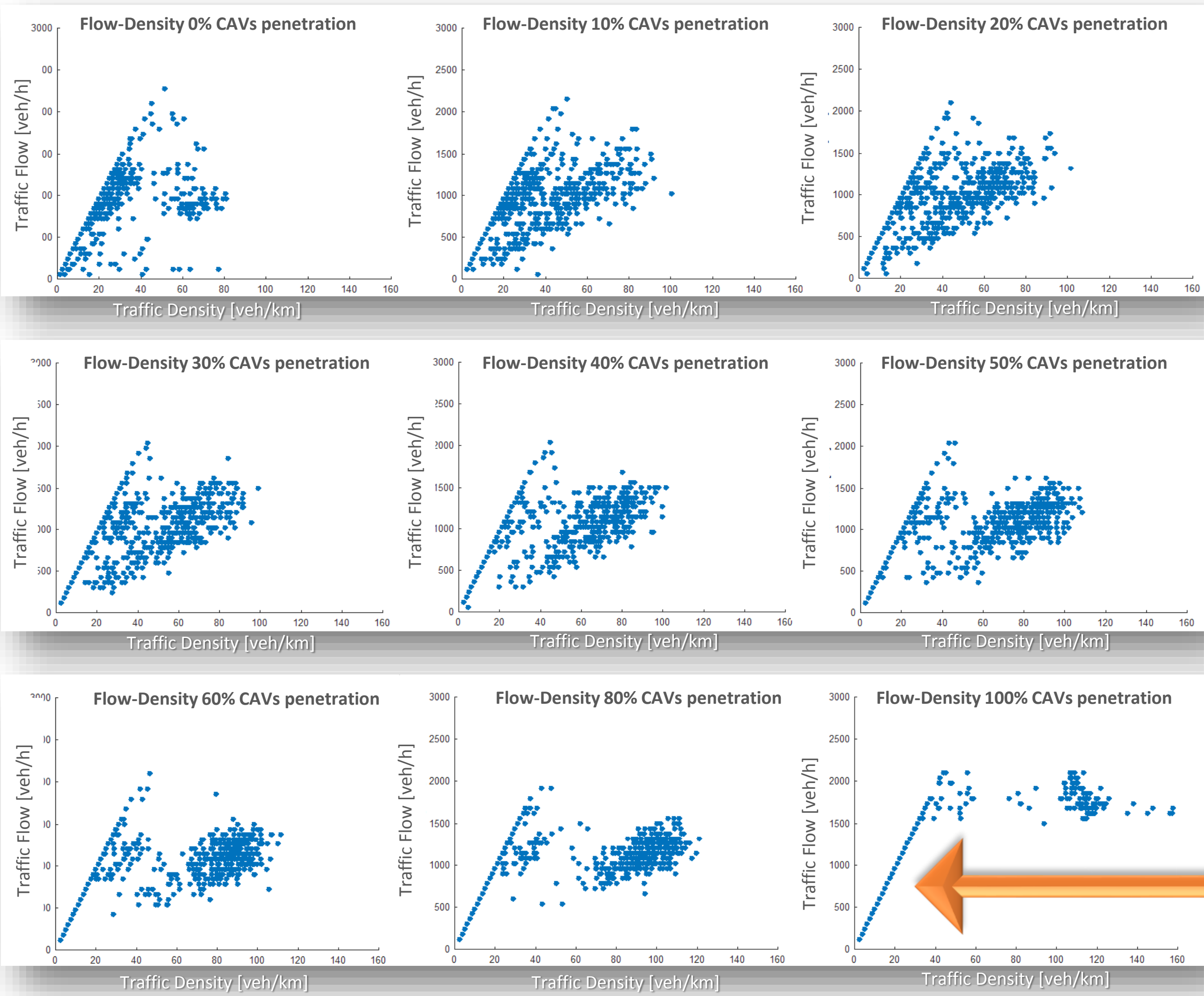
High traffic



Rios-Torres, J; A. A. Malikopoulos, "Impact of Partial Penetrations of Connected and Automated Vehicles on Fuel Consumption and Traffic Flow," (*submitted*)

Partial market penetration assessment – Merging on-ramp

Partial market penetration assessment – Merging on-ramp



Flow-Density

- Low CAVs penetration
  - traffic is scattered
  - congestion can still happen
- Higher CAVs penetration
  - Traffic becomes more stable